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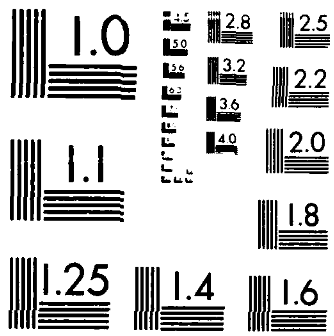
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IMPROVEMENT OF HEAD-UP DISPLAY STANDARDS

Volume III: An Evaluation of Head-Up Display Safety

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A review of the safety aspects of head-up displays (HUDs) is presented. Because of the widespread concern about the use of HUDs during unusual attitudes, particular attention was paid to spatial disorientation and the implications of flying by reference to the HUD during unusual attitude recoveries. It is concluded that the HUD is not inherently unsafe during instrument meterological conditions and is quite suitable for use as a primary flight display. It is clear, however, that current military training for pilots in the use of the HUD is inadequate both in terms of initial pilot training and recurrent training. Any problem with head-up displays is exacerbated by the lack of adequate training. The use of a generic HUD procedures trainer is highly recommended. Orientation (Direction), Flight instruments, instrument, safety

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Summary

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Table of Contents

List of Table and Figures

List of Abbreviations

ADI	Attitude director indicator
AFB	Air Force Base
AFIFC	Air Force Instrument Flight Center
AFM	Air Force Manual
AFWAL	Air Force Wright Aeronautical Laboratories
AGARD	Advisory Group for Aeronautical Research and Development
ALPA	Air Line Pilots Association
CCIL	Continuously computed impact line
CFIT	Controlled flight into terrain
CRT	Cathode ray tube
EADI	Electronic attitude director indicator
FDI	Flight Dynamics, Inc.
FOV	Field-of-view
GPWS	Ground proximity warning system
HD	Head down
ICAO	International Civil Aviation Organization
IFC	Instrument Flight Center
IFR	Instrument flight rules
IMC	Instrument meteorological conditions
INS	Inertial navigation system
IPIS	Instrument Pilot Instructor School
HUD	Head-up display
LCOS	Lead compensating optical sight
LIT	Lead in training
LOSA	Loss of situational awareness
NADC	Naval Air Development Center
NTSB	National Transportation Safety Board
PK	Probability of kill
PVD	Peripheral vision display
RAE	Royal Aircraft Establishment
RAF	Royal Air Force
SDO	Spatial disorientation
TAC	Tactical Air Commant
UA	Unusual attitude
UPT	Undergraduate pilot training

I. INTRODUCTION

The designers of aircraft are rapidly adopting glass cockpit technology where conventional electromechanical and pneumatic instruments are being replaced by cathode ray tubes (CRTs) for presentation of information to the pilot and other crew members. In Addition, head-up displays (HUD) are being adopted as the primary flight reference for instrument meteorological conditions. This technology influx has created the potential for new and unique formats by which information critical to flight and mission success is conveyed to the flight crew.

A. HISTORICAL REVIEW

The HUD is an outgrowth of the reflective gunsight of World War II. In such gunsights, the aiming symbol was generated as a collimated beam of light, projected upwards, and reflected toward the pilot by a semi-transparent mirror placed in his field-of-view (FOV) through the windshield. If the design is correct, the pilot will see the symbols floating in his view of the outside scene. The image of the symbols can be focused to form a virtual image which appears to lie in the same plane as the outside visual scene. From lead-computing gunsights, the next step was to place flight information in the virtual image.

The reasons for providing a head-up display are seemingly intuitive:

- A head-up display can reduce pilot workload when the piloting task requires head-up, outside-the-cockpit flight references.
- Improvements in accuracy and efficiency occur from the overlay of HUD-presented data with the external visual scene.
- A conformal display will allow the pilot to directly assess the aircraft performance.

Much of the early development of HUDs took place at the UK's Royal Aircraft Establishment (RAE) in the late 1950s and early 60s. These early studies indicated that a HUD need not be conformal to the real world, but rather only an approximate overlying of symbols and real world cues was required(1-4). Part of this may have been the result of a lack of technology to reliably generate a conformal contact analog (i. e. no inertial navigation systems, INSs).

The early work at the RAE was based on extensive flight test and simulator experiments. Most of the conclusions were based on a performance metric, that is, the success criteria for a display was based on the minimum tracking error. The ability of the pilot to monitor the display and his own performance was also not usually considered. Naish, in one simulator study, did purposely misguide the subject pilots to a touchdown off the runway(5). He found that the subject pilots tended to ignore the HUD and fly by the real world cues as they became available. Similar experiments were carried out by NASA in the 1970s with similar conclusions(6).

At the present time, HUDs are in operational use on most fighter/attack airplanes. While these HUDs were placed on these airplanes to serve as gunsights or bombsights, pilots have found that they are extremely useful in routine flight. USAF pilots flying A-7D, F-15, and F-16 fighter aircraft report that they use the HUD as an important part of their instrument scan (7). The Navy recognizes the HUD as the primary flight reference for both the A-7E and F-18. In fact, the HUD symbology is the only source of attitude information in the F-18 during instrument flight (other than the standby indicator).

B. AIR FORCE STUDIES

In the mid-1970s, Tactical Air Command (TAC) requested guidance on the use of HUDs from the Air Force Instrument Flight Center (AFIFC,IFC). In the resulting study, IFC found that while the HUD did represent a significant aid as a flight reference, the lack of adequate failure detection; an increased tendency toward spatial disorientation; and inadequate standardization limited HUDs usefulness as a primary flight reference (8).

A later survey attempted to further define some of the problem areas noted in the IFC survey. This study (7) concluded that there appeared to be a dichotomy between useful HUDs and those HUDs which were not useful as a primary flight display. Based on pilot comments, a number of issues were raised:

- The dynamic response of the HUD symbols appeared to be inadequately controlled by the specifications. (Most HUD specifications do not address the dynamic response of the symbols at all.)
- There is a considerable lack of standardization from HUD to HUD in terms of symbology, nomenclature, and operational use.
- Many HUDs had inadequate field-if-view (FOV).
- Most HUDs had inadequate capability to dim the display during night operations.

- There appeared to be a tendency of pilots to report spatial disorientation when flying by reference to the HUD.

Since the publication of this survey, some of these issues have been addressed. The inadequate FOV issue has apparently been dealt with satisfactorily with the advent of diffraction HUDs, although there will probably always be requests from pilots for more FOV. One pilot intereviewed in the survey said, "There is no such thing as too much field-of-view."

The current HUD program was intended to develop new, standardized HUD criteria. As part of this effort, it has developed a design guide to assist the designer of HUDs in ensuring that the next generation HUD will be suitable for the task (9). The design guide also develops guidelines for HUDs intended for use as the primary flight display during instrument meteorological conditions (IMC). Other areas of the current program have addressed the other issues: HUD display dynamics (10); HUD accuracy requirements (11); and symbologies to enhance pilot recognition of and recovery from unusual attitudes (12).

C. HUD SAFETY

A final task of the current program to develop improved HUD criteria was a study of HUD-related safety issues. This report addresses this issue. In actual fact, there are a multiplicity of issues ranging from HUD instrument procedures to spatial disorientation. The following sections will address various aspects of "The HUD Safety Problem."

Recent accident histories of modern tactical aircraft indicate that spatial disorientation (SDO) is a major problem in military airplanes (13-15). Quite often the head-up display (HUD) is blamed for causing the pilot to become disoriented. As is usually the case, blaming an accident or series of accidents on a single isolated cause is overly simplistic.

Nevertheless, it is becoming increasingly obvious that there is a problem. Many factors are involved: aircraft handling qualities, poor head-down instrument layouts, HUDs that are not designed for instrument flight, instrument procedures that do not recognize the effect of the velocity vector, and inadequate instrument training.

II. THE HUD VERSUS "REAL" INSTRUMENTS

Before discussing the effect of HUDs on flight operations, we should first consider exactly what a HUD is and how it differs from traditional flight instruments. As we have stated, the HUD is an outgrowth of early reflecting gunsights. Gunsights began as simple iron rings and developed into a collimated display reflecting from a semitransparent glass (a combiner). The initial reflecting gunsights showed a circle and dot which appeared to float in the same plane as the target.

Two effects were immediate. First, pilots found that they were able to focus on both the target and the sight, rather than having one appear blurred (or as a double image). Second, engineers found that they could move the location of the aiming reticle to allow for target motion and the bullets time-of-flight. The result was the lead-compensating optical sight (LCOS). The next step was to place limited flight information in the HUD -- such as airspeed or altitude. This then graduated to a miniature instrument display, such as was developed by the RAE in the early 1950s.

We can now define a head-up display. A HUD is a display which places collimated flight information in the pilot's forward view super imposed over a view of the real world. This definition disqualifies peripheral vision devices, such as angle-of-attack indexers, rotating barber poles (16), or the Malcomb horizon (17) from being considered HUDs since they do not present collimated images. The need for flight information disqualifies gunsights, such as LCOS or continuously computed impact line (CCIL) displays.

A. COMPARISON

What does a HUD have that makes it unique. Table I shows some characteristics of HUDs and other displays.

The conventional panel has the characteristics of being fixed in position with quite limited capability to be programmed for different phases of flight. Conventional instruments are capable of color coding, such as the blue/brown attitude indicator. They are also useful for displaying systems data. Quite obviously, conventional instruments do not appear in the pilot's view of the real world. The pilot must also look at the instrument to use it. We have indicated a ? for "Can show velocity vector." While no such displays have been produced to our knowledge, they have been considered and tested (18,19). There is no physical reason why such a display could not be produced.

Head down CRT panels have many of the same characteristics of conventional panels. In addition, it is possible to reprogram the same display for different phases of flight. An electronic attitude (director) indicator (EADI) can display different types and amounts of information in cruise, during an instrument approach, or on takeoff. The electronic display can also generate symbology that is an analog of the real world, the contact analog. This has been extended to electronic moving map displays which are analogs of the world when viewed from above. Finally, the electronic CRT display can integrate information (data) from a number of sources. This would include displaying velocity vector.

Peripheral vision displays (PVDs) display data which do not require direct viewing by the pilot. By either changing the display (such as angle-of-attack indexers) or moving a line in the peripheral vision (Malcomb horizon), these displays are intended to bypass the normal cognitive processing and produce a reaction from the pilot. In particular, the Malcomb horizon appears to maintain pilot orientation without requiring a conscious effort on the part of the pilot. While some displays do use color, these are primarily to reinforce a cognitive response following an initial peripheral response. Peripheral vision is not normally considered to be sensitive to colors.

HUDs share some of the characteristics of CRT displays. The primary such characteristics are the abilities to be programmed. to time share, and to display integrated information from a variety of sources. The significant differences are the presence in the direct view of the outside world (which is self-evident) and the monochromatic nature of HUDs. While color HUDs have been discussed, it seems unlikely that a HUD will ever have the degree of color coding available in head-down instruments, whether conventional or electronic. For example, one can not employ blue to show pitch angles above the horizon because of a lack of contrast with the sky. The advent of diffraction HUDs makes color HUDs with more than two colors unlikely. (Most head-down CRTs use three colors to generate the images.) This will limit the number of color cues available in HUDs of the future. One should not look for a complete color HUD.

Perhaps the most compelling difference between HUDs and all other displays is the ability of the HUD to display conformal images which exactly overlie the corresponding objects in the pilot's view.*

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* Parenthetically, one task of the present HUD study was designed to address the issue of how accurately does a runway symbol have to be placed to produce an acceptable HUD. To this end, an in-flight experiment was conducted using the USAF variable stability NT-33A aircraft equipped with a programmable head-up display (11).

In 1966, Col. Klopfstein, a French test pilot, developed a HUD symbology which presented both a contact analog of the runway environment and a format to directly assess the current state of the airplane in terms of the variables, angle-of-attack (ALPHA), flight path angle (GAMMA), and pitch attitude (THETA) (20). This display, developed by Thomson-CSF in France allowed the pilot to fly the airplane by reference to the HUD with no numerical data displayed. Figure 1 shows the format. Klopfstein's approach was to make use of the difference between flight path angle (velocity vector in our terminology) and the aircraft pitch attitude. The difference is exactly the angle-of-attack:

ALPHA = THETA - GAMMA

While Klopfstein's symbology was difficult to follow -- the coding differences between various symbols was insufficient for pilots to easily distinguish one from another -- his approach allowed the use of a conformal display of the three flight parameters most of interest to the pilot. ALPHA information ensures adequate aircraft performance, GAMMA information shows where the airplane is going through the air, and THETA information shows the traditional aircraft attitude. Klopfstein insisted that no "number" were necessary, and in fact none were to fly the airplane well within accepted tolerances. However, the absence of numerical data limited the acceptance by operators and certification authorities.

Nevertheless, for the first time pilots had a display which identified the three major parameters in aircraft control and let the pilot understand this in the scale of the real world -- not as abstract numbers on a dial. Col. Klopfstein's contribution is too valuable to reject along with his symbology.

In the 1970s, Dassault developed a similar symbology to incorporate the best features of the Klopfstein display with numerical data added. The result was the PERSEPOLIS display (21).

These displays both make use of the fundamental relationship between ALPHA, GAMMA, and THETA and use air mass data. The reason for this is that airplane performance is based on air mass data -- not on inertial velocities.

One other display of note is the display on the Navy A-7C/E and the Air Force A-7D. While this display uses inertial data to generate the velocity vector, the angle-of-attack error is shown by a depressed pitch attitude symbol. Because the relationship between the three variables is present (clouded by the use of inertial data and very limited pitch information), the basic data of the Klopfstein approach is present. Some A-7 pilots have commented that using the standby reticle as a pitch reference allows them to check the angle-of-attack display. While the concept is not taught formally, it appears that A-7 pilots absorb the relationship through experience.

Navy A-7 pilots apparently absorb enough of these concepts to improve their no-HUD landing performance compared with their counterparts (A-7A/B) with no HUD experience. A Navy study indicates that A-7C/E pilots flying night carrier approaches without a HUD performed better than A-7A/B pilots (22). The conclusion is that having HUD experience improves pilot performance after the HUD is taken away.

B. VELOCITY VECTOR CONSIDERATIONS

The HUD also presents a new flight parameter -- velocity vector. This is a projection of where the airplane is going. The velocity vector is not available on any head-down panel in service today. The velocity vector, particularly if derived from high quality inertial data provides the pilot with an instantaneous depiction of the airplane's trajectory. There are, however, two problems with the use of the velocity vector as a control instrument. These are the effect of large angles of attack and the effect of air mass data versus inertial data.

The velocity vector can be calculated in two fashions: air mass using pitch attitude (THETA) and angle-of-attack (ALPHA); and inertially using vertical velocity Vz and horizontal velocity Vx. The first approach calculates the flight path angle (GAMMA) using the expression GAMMA = THETA - ALPHA. The second approach calculates the flight path angle as GAMMA = arctan(Vz/Vx). Note that we are assuming no lateral motion to simplify the discussion.

There are two myths that must be dispelled: First that inertial data is better than air mass data. This is not so. Air mass data is clearly supperior for determining and control airplane performance. These aircraft are becoming increasingly susceptible to windshear and downburst encounters. Some authorities recommend the use of air mass data vice inertial data to maximize the recovery during these encounters. Inertial data is clearly better for navigational purposes (including "micronavigation." They each have their place for HUDs.

The second myth is that one must have a HUD to use velocity vector. This is also not true. Certainly, velocity vector data is much clearer and generally useful when shown on a HUD, but air mass data does reflect aircraft performance and would be equally useful head-down. Many wind shear encounters for transports are recognized more by the effect on velocity vector than by the fact that they are shown on a HUD.

C. AIRCRAFT AND MISSION CHARACTERISTICS

1. Aircraft

The flying qualities of many modern fighter aircraft does not make these airplanes easy to fly on instruments. The most characteristic feature of modern control systems is the absence of any speed feedback through the control column. This, coupled with a trim system designed to help maintain vertical acceleration (Gs) rather than airspeed, makes instrument flying much more difficult.

A second feature on these modern airplanes is their extreme maneuverability. While this is desirable during ACM, it is not an instrument flying enhancing quality.

These two characteristics are not fundamentally different for modern fighters, but they do make instrument flying more difficult.

2. Instruments

The avionics suite of modern tactical airplanes is very complex. There is an increasing tendency to placing weapon or mission information in the center of the instrument panel in the place formerly reserved for the attitude indicator. The attitude indicator has been relegated to a remote part of the instrument panel, sometimes between the pilots legs. Space considerations force the attitude indicator to be as small as possible, not as large as possible. It is not possible, with today's designs, to locate the attitude indicator in the center of the panel. The lack of space behind the panel forces the designer to locate only switches in this primary region of the panel -- not instruments needed to fly the airplane.

3. Mission

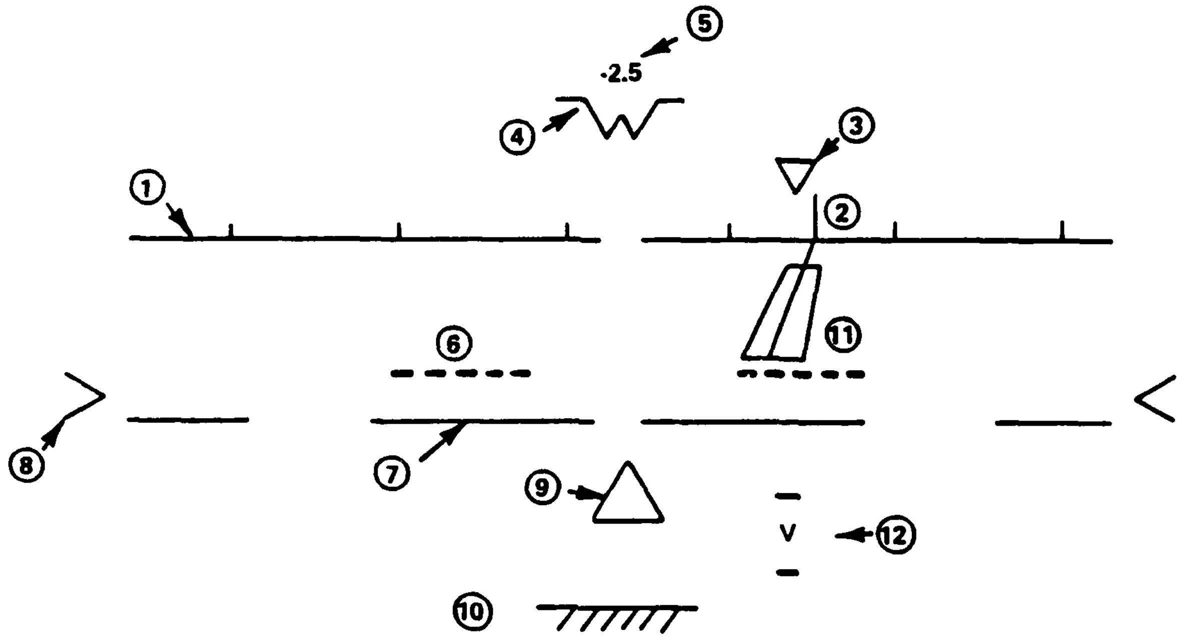
The mission workload on the modern tactical airplane is very high. The need to program the mission computer, fly the airplane, keep aware of the mission environment, etc. all have their effect. Many of the problems encountered during LOSA accidents and incidents are directly related to workload.

Table I

DISPLAY CHARACTERISTICS

Display Characteristics	Conv. Panel	CRT (HD) Displays	PVDs (a)	HUDs
In Forward View			X	X
Collimated				X
Color Coded	X	X		
Programmable		X		
Time Share		X		
Integration Possible		X		X
Foveal Cues	X	X		X
Peripheral Cues			X	?
Useful for Systems	X	X		
Contact Analog Possible		X		X
Conformal Possible				X
Can show Vel Vector	?	X		X

(a) Peripheral vision displays, such as angle-of-attack indexers, Barber poles, Malcomb horizons, etc.



1. HORIZON LINE WITH 2 DEG. HEADING MARKS (OVERLAYS REAL HORIZON).
2. EXTENDED RUNWAY CENTERLINE.
3. TRACK MARKER.
4. WATERLINE SYMBOL.
5. SELECTED FLIGHT PATH ANGLE (ANGLE BETWEEN HORIZON LINE AND SELECTED FLIGHT PATH MARKER = GLIDE PATH ANGLE).
6. SELECTED FLIGHT PATH MARKER (DEPRESSED BELOW HORIZON LINE AT GLIDE PATH ANGLE).
7. AIRMASS FLIGHT PATH MARKER.
8. POTENTIAL FLIGHT PATH MARKER (AIRSPEED INCREASING. AIRSPEED INCREASE WILL STOP IF THRUST IS REDUCED TO LOWER POTENTIAL FLIGHT PATH MARKER TO ALIGN WITH FLIGHT PATH MARKER, OR IF FLIGHT PATH MARKER IS RAISED TO ALIGN WITH POTENTIAL FLIGHT PATH MARKER).
9. ANGLE OF ATTACK TRIANGLE. (ANGLE OF ATTACK LESS THAN COMMAND. COMMAND ANGLE OF ATTACK IS ACHIEVED WHEN APEX OF TRIANGLE IS TOUCHING THE FLIGHT PATH MARKER).
10. LIMIT ANGLE OF ATTACK. (LIMIT ANGLE OF ATTACK IS ACHIEVED WHEN LIMIT SYMBOL IS ALIGNED WITH FLIGHT PATH MARKER).
11. SYNTHETIC RUNWAY (THRESHOLD AT GLIDE PATH INTERCEPT POSITION).
12. HEIGHT ABOVE TOUCHDOWN INDICATOR.

Figure 1

Klopfstein HUD Format (Reference 20)

III. The HUD IN SPATIAL DISORIENTATION

A. BACKGROUND

In recent years, an increasing concern over the problem of spatial disorientation (SDO) in modern jet cockpits has been the issue of aircraft accident investigators (13-15). While spatial disorientation has been a difficult fact of life for as long as pilots have flown in clouds, the modern problem was first voiced by Barnette (8) who performed a survey of HUD pilots for the USAF Instrument Flight Center (IFC). This survey indicated that approximately thirty percent of pilots surveyed reported an increased tendency towards vertigo or spatial disorientation. A later study, by Newman, confirmed, these findings (7).

The problem appears to have become more visible in recent years. Conferences to deal with the issue of modern day spatial disorientation have been called at Luchon (22), at Langley AFB (13), at the Pentagon (14) and at Wright-Patterson AFB (15).

While SDO is often considered to be a fighter issue only, in fact it occurs, albeit with somewhat less frequency, in transport airplanes (23).

Spatial disorientation is only part of the problem. Many accidents involve a loss of awareness on the part of the pilot as to the proximity of the ground (24), the geographic location of the airplane (25), the performance of the airplane relative to the terrain (26), in addition to the classic SDO upset. Examples of each are noted. Again, both transport aircraft and tactical fighters can be involved. The generic term loss of situational awareness (LOSA) can be used to describe the overall problem. SDO is but a subset of LOSA.

B. SPATIAL DISORIENTATION

Spatial disorientation (SDO) has been a constant problem in aviation since the first flights into a cloud (probably resulting in a spiral dive out the bottom of the cloud). Spatial disorientation has been characterized by Benson as "a wide variety of experiences occurring in flight in which there is a defect in the aviator's perception of the attitude or position of his aircraft or where conflicting perceptions give rise to confusion or uncertainty." Sometimes the term spatial misorientation is given to situations where the pilot has a definite but incorrect perception of his attitude or position.

A good primer to review for the overall discussion of spatial disorientation in flight is Benson (27). Additional discussion can be found in Reference (22).

Orientation cues are perceived by the visual sense, by the vestibular organs of the inner ear as well as by the senses of touch and kinesthesis. The peripheral visual cue is generally considered to be the most important of these. If the perceived bodily orientation is not appropriate for the desired function (walking, standing, sitting, etc.), appropriate motor responses are initiated to return the body to the desired orientation.

On the ground, these various senses are usually in agreement. In flight (and other disorienting environments, such as skin-diving) the senses may return conflicting perceptions. These conflicting perceptions may all be incorrect. In an airplane during flight in clouds or at night, the pilot must rely on his instruments to determine the actual aircraft orientation. In general, his orientation senses do not provide reliable perceptions to determine his orientation in flight.

Normally the maintenance of orientation by the pilot in flight is a learned response requiring some cognitive activity. (For the purposes of this discussion, we shall assume instrument flight unless otherwise specified.) These learned responses are called instrument flying skills and differ from the terrestrial orientation skills developed since childhood. In fact, instrument skills require that the terrestrial orientation skills be subordinated to a cognitive response.

The primary orientation sense in visual flying or in basic terrestrial orientation is the visual sense of the horizon. In instrument flight, however, this input is not present (In some cases it may be present, but incorrect, such as with sloping cloud tops or mountain ranges). The pilot obtains his orientation via the visual sense but via the focal visual mode by fixating on the attitude and other instruments and determining his attitude by cognition. There may be some peripheral visual input if the attitude instrument horizon line is sufficiently large and sufficiently obvious.

The information presented by the aircraft instruments is not in a proper format to use his terrestrial orientation skills, so the pilot is forced to use his instrument flying skills to maintain orientation.

Other orientation cues are those perceptions from the vestibular, touch, and kinesthetic senses. Generally these do not provide useful information during instrument flight and often provide erroneous cues. The pilot is subjected to angular rotations and accelerations and to linear accelerations that he will not experience on the ground. These cues usually are not appropriate for orientation. As part of his instrument learning, the pilot must learn to suppress these inappropriate cues and rely on

the data provided from the aircraft instruments through his visual senses.

Much has been written about specific misleading vestibular and kinesthetic cues that cause misorientation. Some of these deal with interpretations of linear accelerations resulting in perception of a changing vertical orientation. Others deal with low level angular accelerations and a perception of no angular motion if a steady rotation is senses. Again, these can be amplified in a spatial disorientation source, such as Benson(27).

The sense of touch is not normally considered to be a useful orientation cue during flight. This is not correct. Touch in the form of stick forces (and to a limited extent stick position) provides an important feedback cue of airplane speed which in turn provides some input into orientation. Aural cues can also provide some sensory input of aircraft speed from the aerodynamic noise over the canopy. It also can provide cues as to engine thrust level.

In general, spatial disorientation will occur if conflicting sensory inputs are perceived and these conflicts are not resolved by the pilot. Spatial misorientation will result if an incorrect sensory input is perceived and treated as correct by the pilot.

Some perceived sensory information is particularly troublesome with respect to spatial disorientation (SDO). Visual nystagmus is an important reinforcement for SDO. This problem caused by involuntary eye movements accompanying head motion may have particular HUD-related problems. Rapid changes in eye accommodation has been cited as a potential source for SDO (28). These may also contribute to HUD-related SDOs.

Human expectation of what the perceived sensory inputs mean may contribute to SDO. Such problem areas as perceiving accelerations as tilting, apparent motion of fixed lights, and the effect of tilting cloud tops are examples of expectation problems.

Finally, pilot confidence in the perceived data is cited as a contributing factor in maintaining awareness. If a pilot lacks confidence in his instruments or in instrument flying skills, he will be more susceptible to SDO.

C. LOSS OF SITUATIONAL AWARENESS

A more generic problem of interest is loss of situational awareness (LOSA). LOSA includes spatial misorientation and disorientation as subsets, but also includes those instances where the pilot is aware of his orientation, but either not aware of his position or of the proximity of the ground or other aircraft. A leading cause of these accidents is channelization of attention and failure to monitor the progress of the flight.

The classic cases of LOSA deal with the controlled flight into terrain (CFIT) accidents where the airplane flies under pilot control into the ground. Clearly in this situation, the pilot was not suffering from SDO, but rather for some reason either didn't know his position or was unaware of the proximity of the ground. Reference (24) describes such an accident. This accident provided the impetus for the addition of ground proximity warning systems (GPWS) to US air carrier transports.

In this classic CFIT accident, the pilot knew his position reasonably well, but was confused about the minimum safe altitudes to be flown during an instrument approach. In the CFIT accident, it is usually stated that the airplane flies under complete control into a mountain. These accidents have been virtually eliminated from civil air carrier records since the implementation of GPWS.

In another type of LOSA accident, the pilot of a RAF Jaguar became confused as to the performance of his airplane. Although he was well aware of the ground, confusion between the HUD presentation and the panel instruments led him to a loss of awareness of the aircraft's performance (26).

The causes of LOSA usually training related -- complacency, confusion, lack of comprehension, or excessive workload and channelized attention. One of the first priorities of a pilot is to remember that "the ground has a Pk of one."

D. EFFECT OF THE HUD

Both Newman (7) and Barnette (8) conducted surveys of pilots flying HUD-equipped airplanes. Both surveys report that a sizable fraction -- thirty percent in reference (7) -- report an increased tendency toward SDO caused by the HUD. In a later survey, Newman and Foxworth (29) report a lower tendency toward SDO by pilots flying F-18 and Mercure airplanes. Newman and Foxworth attribute this decline (14% of F-18 pilots, none of Mercure pilots report SDO) to training or to better integration of the HUD into the cockpit. In fact, the reason is very likely better integration in the case of the F-18 and better training in the case of the Mercure.

HUD-induced SDO is reported to result from a number of inflight scenarios. The most common report is an increased tendency while flying in-and-out of clouds. Other instances include extreme maneuvers while using the HUD for flight reference, such as night pull ups from the target, unusual attitude recovery, or air combat maneuvering (ACM). These are the traditional areas for spatial disorientation in general, not just in HUD-equipped airplanes.

There may be several factors causing this potentially serious problem in the use of HUDs for instrument flight. The pri-

mary cause of SDO is conflicting orientation cues. According to Tyler and Furr (30), the primary cause of SDO is reduced visual cues, not an abnormal stimulation of vestibular cues. What we are seeing in HUD flying is an inability of the pilot to recognize when he is in an unusual attitude (UA) and then to recover using the HUD. The problem arises from a variety of causes. These causes (in no particular order) are

- Lack of color codes to identify erect from inverted flight;
- Lack of texture cues in the HUD similar to those found in attitude indicators to identify erect from inverted flight;
- Excessive amount of data present in the HUD in the form of digital data boxes, etc., which are useful during selected phases of flight, but do not assist during UA recovery;
- Difficulty in assessing rate information with digital airspeed and altitude presentations;
- Small field-of-view (FOV) combined with full scale angles (which are helpful during normal flight) which make assessment of the overall situation difficult;
- Accommodation traps in the HUD symbology or in the combiner structure which cause the pilots eyes to accommodate to a distance much less than optical infinity;
- Use of the velocity vector (GAMMA) as a control parameter rather than as a performance parameter.

Any solution to enable the HUD to be useful during UA recognition or recovery must address these topics. It must be pointed out that many of these issues apply equally to electronic attitude displays (EADIs, etc.).

1. Lack of Erect versus Inverted Cues

The conventional attitude (director) indicator (ADI) uses black (or brown) and blue (or light grey) hemispheres to distinguish erect from inverted flight. The ADI also provides patterns on one or both hemispheres to simulate ground texture or clouds. Most also use a stylized airplane symbol to emphasize aircraft attitude.

The HUD, on the other hand, is limited in that it must use monochromatic lines and avoid texture cues which might block ex-

ternal visual cues. It is unlikely that color HUDs will be able to provide sufficient color contrast in the near future. It is also impractical to expect the blue or brown colors denoting sky or ground to be available for HUDs regardless of technology, because a blue symbol would not be clearly visible against the sky and a brown symbol would not have sufficient contrast against some terrain features.

In this respect, HUDs are similar to first generation artificial horizons. It is interesting to remember that, originally, unusual attitude recovery called for the pilot to roll to the nearest horizon. This could leave the pilot erect or inverted, however, the aircraft would be stabilized.

In place of color coding the HUD, other approaches must be taken. One is to use solid versus dashed lines above and below the horizon. Plus and minus numbers are used as well. It is unlikely that these can be entirely successful, by themselves, during the dynamic situation of an unusual attitude.

Other approaches suggest include asymmetric pitch lines (inverted flight places these lines on the other side of the HUD). This would make it easier to recognize erect from inverted flight, but would do little to assist in identifying extreme nose-up from nose-down attitudes. A similar, but less extreme format was proposed by Taylor of the RAE.(31-32)

Different pitch scalings above and below the horizon have been suggested to aid in identifying nose-high and nose-low situations. The F-18 HUD uses slanted pitch lines at large pitch angles to indicate the direction to the horizon. Another cue could be a bank index (a sky or ground pointer). Still another would be to add the words "DIVE" and "CLIMB" as is done on many ADIs.

2. Clutter

During UAs, HUD clutter can prevent the pilot from interpreting the cues needed for prompt recognition and recovery. Clutter has been defined in a draft FAA Advisory Circular as "A cluttered display is one which has an excessive amount of information in the number and/or variety of symbols, colors, and spatial position relationships. A large fraction of this information may be pertinent to the task at hand, but if an evaluation shows that the secondary information detracts from the interpretation necessary for the primary task, or increases the display interpretation error rate, irrelevant or lower priority information should be removed."(33) The two-and-one-half degree pitch line spacing on the early F-16 HUD has been criticized in this regard. Excessive data has also been criticized. In extreme situations. almost complete declutter (even to the point of deleting required parameters, such as heading) may be required.

3. Lack of Rate Information

The use of digital displays has been criticized by some pilots in making the determination of rate information difficult. This may be more of a problem with determining airspeed rate than altitude rate, since the velocity vector will allow the pilot to control his altitude rate during normal flying. It is not clear how this will or will not affect UA recognition and recovery. Possibly the flight path acceleration cue proposed by the French could be of some use here (20-21).

4. Pitch Scaling

It can be difficult to assess the situation using a full scale but limited FOV display. The conventional ADI is cruder, but its compressed scale makes recovery easier. Studies have been performed to examine the benefits of compressed pitch scaling during large amplitude maneuvers (34). These results indicate that pitch scale compression can be a help during air combat maneuvers (ACM) or acrobatics.

Early HUD studies in the United Kingdom also showed that a slight pitch scale compression produced tighter approach tracking than one-to-one scaling (4,35). Compressed pitch scales may help during UA recognition or recovery as well. They have been recommended by Freiburg as well (36).

5. Accommodation Issues

The issue of accommodation traps has been raised by Roscoe and others (28,37-38). Briefly, the argument is that the HUD symbology, in spite of being collimated, will not allow the pilot's eyes to accommodate to optical infinity but will focus much closer to a distance approximating the dark focus point (perhaps one meter in front of the pilot's eye). This, they assert, will cause large shifts in accommodation when the pilot fixates on objects in the real world. This rapid shift in accommodation between HUD images and real world images can be a major cause of vertigo.

We do not accept this argument completely. Based on interviews with operational pilots flying HUDs, Newman (7) found virtually no mention of eye discomfort, focusing problems, or anything resembling accommodation difficulties. Subjectively, we find that flight in rain in a HUD-equipped airplane allows much clearer view through the HUD combiner than around it. When the HUD symbology is turned off, view through the combiner or around it is equally clear (about the same as the previous view around the combiner. The conclusion, a subjective observation, is that the symbology makes the real world clearer and more in focus. We will suggest that the raindrops and streaks on the windshield act

as accommodation traps to a eye-windshield distance and that the HUD symbology act as traps to a further distance.

In any event, the resulting accommodation distance would be at least as far as the conventional instruments and there have been no suggestions to date that changing from head-down instruments to the real world causes disorientation.

A more subtle form of disorientation can result from the narrowing of the visual field as the eye accommodates to the dark focus point. This may produce errors in judging distance and angles to an outside visual target (39). This disorientation has no bearing on the issue of solid instrument conditions (IMC).

6. Use of GAMMA versus THETA

One potential problem is the practice of pilots using the velocity vector as a control parameter. During normal flight, this presents no problems, but during UAs, particularly at large angles-of-attack (ALPHAs), this can create situations where the pilot needs to push, but is pulling because of the extreme negative GAMMA.

During discussions with operational fighter pilots during this and previous studies (7,29), it appears that they have only a superficial understanding of the implications of using GAMMA as a control parameter rather than THETA. Some HUDs do not even display THETA.

The A-7C/D/E HUD is often criticized for having the ALPHA display "backwards." This was designed to emphasize the unique relationship between THETA, GAMMA, and ALPHA. The Klopfstein and PERSEPOLIS HUDs, designed for transport airplanes made particular use of this relationship (20-21).

E. HUD SYMBOLOGIES FOR ENHANCED UNUSUAL ATTITUDE RECOVERY

Based on results obtained in Reference (12), we can make some recommendations for HUD formats to minimize the pilot's likelihood of entering into an unusual attitude and maximizing his likelihood of recovering from the UA. It is to be remembered that these results are based on simulation, not flight.

1. Pitch ladder cues

The benefit of complete lateral asymmetry was not shown by this study contrary to what was expected from Taylor's studies (31-32). In fact, the lateral imbalance proved distracting to the pilots. The F-18 pitch ladder with slanted pitch lines pointing to the horizon was preferred by the subject pilots. It also showed a slight improvement in reaction time during UAs.

The subjects also complained about the controlled precession as the aircraft pitch passed through the zenith or the nadir (90 degrees pitch up or down). This is an artificially induced action intended to emulate the action of early attitude indicators as they approached gimbal lock at the 90 degree up or down attitude. This makes controlled flight through these points quite difficult and is a means of inducing unusual attitudes for practice (7). There is no need to maintain this controlled precession in any future electronic attitude indicators or HUDs. It was incorporated in an attempt to mimic a shortcoming of mechanical instruments and has no place in electronic displays.

2. Scales format

The conventional digital airspeed and altitude scales appear to be quite satisfactory. The concept of automatic declutter or a switch from analog to digital does not appear to be fruitful. (This applies to airspeed and altitude scales.)

There does not appear to be a need for rate information during UA recoveries. A circular index indicating tens of knots or hundreds of feet (the minute hand) did not appear to help during UA recoveries. It is worth examining further for routine instrument flight, however.

At the same time, the pitch ladder should be redrawn to enhance heading awareness at extreme pitch attitudes. Freiburg and Holmström evaluated an ADI with enhanced heading information near the ninety degree pitch up or down point (40). A similar approach would enhance HUD attitude awareness at extreme pitch attitudes.

3. Bank information

The presence of bank information had a very positive effect on both subjective and objective results. An arrow on the velocity vector (Augie Arrow) was clearly preferred subjectively and ranked well in objective data.

It is not clear if a sky pointer or a ground pointer is preferred for a bank scale. It should be compatible with the pointer on the head-down ADI as installed on the aircraft. It should also be compatible with the arrow on the velocity vector (the Augie Arrow), if incorporated. This would suggest a sky pointer. However, a ground pointer at the bottom of the FOV and a sky pointer on the velocity vector did not pose a problem when displayed on the same format.

The use of a sky pointer requires that the heading scale be modified to avoid interference. Since civil HUDs use the horizon as the heading scale, this should be followed as well with a sky

pointer. A digital heading box above the waterline to show digital heading could be helpful. The Flight Dynamics HUD for the Boeing 727 uses a similar approach with some success (41).

4. Pitch scale compression

The use of compressed pitch scaling was well received subjectively by the evaluation pilots. The use of two-to-one compression either automatically selected or full time appears to be a likely candidate for UA recovery enhancement. It appears that all non-ground referenced modes would be likely candidates for full-time two-to-one scaling. It is not clear if air-to-ground modes would benefit from such a choice.

It is clear that the use of compressed pitch scaling will require attention to the difference in angle between the pitch symbol (waterline) and the velocity vector. On most HUDs, the waterline is fixed in the FOV and the pitch ladder and velocity vector drawn relative to it. If compressed pitch scaling is implemented in operational HUDs, it might be more desirable to draw the pitch ladder so that the horizon overlies the real world horizon or draw the pitch ladder such that the velocity vector symbol overlies the aircraft°s actual velocity vector. Any external target cues should overlie the actual location as viewed by the pilot.

The Flight Dynamics HUD uses a variable pitch compression for extreme nose-high or nose-low attitudes. No problems were encountered during a simulator evaluation of this HUD (42).

5. Automatic deletion of velocity vector

One of the concerns during UAs is that the pilot will misuse the velocity vector and pull on the stick when already at a high angle-of-attack. One approach to this problem is to delete the velocity vector at large angles-of-attack. This format was rated highly by the subject pilots and had the best objective scores in every category. As implemented in operational HUDs, the velocity vector should be deleted when the angle-of-attack reaches a value where further pull should be discouraged.

If an Augie Arrow or angle-of-attack index is shown, they should be transferred to the waterline when the velocity vector is deleted.

IV. TRAINING ISSUES

With our much more severe operating requirements for the pilot -- the use of a HUD with non-traditional data, airplanes with novel handling qualities, poor instrument layouts, and a demanding workload environment, we would expect that the pilot training in these areas would be enhanced, particularly in the area of basic instrument training and prioritization of tasks. Unfortunately, this is not true.

A. CURRENT TRAINING

Air Force pilots are generally not as well trained in basic instrument flying today as they were several years ago. There is more to learn and less time to learn it in. Pilots graduating from undergraduate pilot training (UPT) today have approximately 12 hours of instrument flying time in airplanes and about thirty hours in simulators. Interestingly, this is not enough to qualify them to fly a Cessna 150 under IFR in civilian operations.

What is, perhaps more critical, is the almost complete lack of emphasis on flying by means of electronic displays, particularly the HUD. There is no question that the techniques useful in HUD instrument flying are different than those useful in panel instrument flying (so-called vector instrument flying versus attitude instrument flying). At present, the only guidance offered by the USAF on using HUDs for instrument flying is cautionary. Yet, admittedly, most pilots find the HUD works for them most of the time and works quite well. As a result they use it and teach themselves how to fly. Unfortunately, in some areas (such as the high ALPHA unusual attitude described above) the system breaks down.

B. HUD TRAINING

There is concern expressed among the more experienced pilots that teaching using the HUD will make the pilot dependent on the HUD. We disagree. The pilot will become no more dependent on the HUD than he is dependent now on the attitude indicator. Further, a Navy study indicates that having a HUD available makes pilots perform better when the HUD is not available (22). This study used Navy A-7 pilots, half of whom had flown the A-7A/B without a HUD and half who had flown the A-7C/E with a HUD. When flying simulated night carrier landings without a HUD, the A-7C/E pilots performed better. These results argue against the concept of a pilot becoming over-dependent on the HUD.

We have already discussed the need for the pilot to learn to make small corrections and to not be overwhelmed by the apparent large amount of movement of the HUD symbols. Subjectively, we had an early HUD instructor who would admonish us to "fly loose" We have also observed a tendency for pilots to over-zealously concentrate on minimizing airspeed and altitude errors -- down to the last knot or foot -- if digital data is provided. New pilots must be trained to avoid this.

Newman's earlier study (7) indicates that it takes a pilot about 300 hours to learn to use the HUD and associated systems. It would be interesting to see how fast he could learn given suitable instruction and how well he would understand.

The French domestic airline, Air Inter, uses a HUD-equipped transport, the Mercure. Their HUD training syllabus takes four or five days devoted to the HUD alone (43). This training occurs after the pilots have about 200-300 hours on the airplane. Much of the training is simulator training which emphasizes the effect of winds and failure states. The system on the Mercure is an air mass HUD so the effect of winds is not obvious to an untrained pilot and could be confusing until he understands what the data means. The simulator training begins with a normal no-wind approach and then follows with an approach with a ninety knot wind to make it quite clear to the pilot what is happening. Air Inter and Swissair have the most advanced HUD training today (albeit the only serious HUD training).

The French do not cover one area seen as a problem. This is how to look "through" a HUD. The skill can be likened to learning how to look "through" a gunsight when learning to shoot or looking "through" a microscope keeping both eyes open. This process is self-taught at present (perhaps those pilots who are anti-HUD never really learned how to do this). This skill requires an airplane and can not be done in a simulator.

In personal experience with HUD flying, we have found that the ability to separate external visual cues and internal HUD cues is the main form of learning that is experienced during early HUD experience. Additionally, pilots new to HUDs must learn to rescale their inputs. The motion of the HUD cues is perceived to be much more rapid and frantic than the conventional instruments. New HUD pilots have a greatly increased workload trying to overcorrect these apparent large excursions from nominal flight. This is also evident with those HUDs having digital airspeed and altitude scales. These problems disappear with HUD experience.

The HUD (and electronic attitude displays in general) present additional difficulties to the pilot -- difficulties not found in conventional panel instruments. The HUD, in particular, does not present a pilot with a clear presentation of pitch attitude. The HUD has no color cue to show the difference between nose high and nose low as does the conventional ADI. The lines

are perceived as being identical (even though nose low lines are dashed.) This makes recognition of aircraft orientation in unusual attitudes difficult and will tend to delay recovery.

The HUD also presents a new flight parameter: velocity vector. This is a projection of where the airplane is going. The velocity vector is not available on any head-down panel in service today. The velocity vector, particularly if derived from high quality inertial data provides the pilot with an instantaneous depiction of the airplane's trajectory. There are, however, two problems with the use of the velocity vector as a control instrument. These are the effect of large angles of attack and the effect of air mass data versus inertial data.

When the pilot flies using GAMMA as a control parameter, he is in effect using the vertical velocity as a control parameter. This produces acceptable results in most instances. Unfortunately, when ALPHA is large or is changing, the use of GAMMA as a control variable can result in incorrect control inputs. The same problem would result if a pilot used vertical velocity as a longitudinal control parameter in contravention of AFM-51-37 (44).

The situation would become the most extreme in a high angle-of-attack unusual attitude recovery. The aircraft nose would be up (above the horizon) while the trajectory would be down (very much below the horizon). The pilot, overtrained on using GAMMA as a control parameter would try to recover by pulling on the stick thus aggravating the already high angle-of-attack. The correct recovery would be to lower the nose (to decrease the angle-of-attack) and add thrust to minimize loss of altitude. Use of head down panel instruments would produce the correct response (assuming the pilot did not attempt to use vertical velocity as a control parameter).

C. WHEN TO INTRODUCE THE HUD

It is not clear when the HUD should be introduced to the pilot -- early in his basic training or later as part of the aircraft checkout. Current US military practice is to introduce the HUD as part of the aircraft checkout. A strong case could be made to introduce the pilot to the HUD as soon as possible -- in primary or basic training -- since many new pilots will only be flying HUD and electronic display equipped airplanes throughout their careers. The Navy study cited above indicates that the other pilots (not flying HUD and electronic equipped airplanes) will actually have an easier task adapting to the "round dial" airplanes than today's HUD pilot has adapting to the HUD.

The most advanced HUD training at present is being conducted by Air Inter and Swissair. Clearly, these two airlines feel that simultaneous introduction of a new airplane and a new concept of flying (the HUD) is too much at once. Air Inter delays introduc-

tion of the HUD for several months after the pilot becomes qualified on the airplane. This is one approach. It does mean that pilots who are already HUD-qualified on another airplane will not be able to use this background from the start or will require a different check-out syllabus.

A second approach, which make more sense, it to introduce the HUD earlier. A dedicated HUD instrument course would outline the special techniques of HUD instrument flying. This could be accomplished in a trainer or in a simulator. The Canadian Forces are examining the concept of a HUD-equipped instrument trainer (Canadair CT-114) to teach the pilots how to fly instruments using the HUD prior to their checkout in HUD-equipped fighters. Pilatus Aircraft is marketing a HUD equipped trainer, the PC-9. At this writing, several have been sold to third world air forces. Other air forces are considering using HUDs during pilot training as well.

D. THE HUD IN BASIC TRAINING

There is a place for a HUD during initial pilot training. First, with most new airplanes going to the glass cockpit, it makes more sense to start the pilots on electronic instruments from the start rather than conventional instruments. This will minimize the need to unlearn round dial skills and then relearn the basic electronic instrument skills.

The argument is that the pilot will become "overdependent on the HUD." This is a specious argument. As we have seen earlier, based on Navy experience, having HUD experience helped the pilots' performance when the HUD was no longer available. This does not appear to be "overdependence." (We also do not seem to worry about pilots becoming overdependent on the ADI.)

Another strong argument in favor of having a HUD during initial pilot training would make use of the ability to display ALPHA, GAMMA, and THETA directly in a full scale picture. Based on 1200 hours of primary instruction, we feel that this would be a very valuable training tool for UPT students.

E. THE HUD PROCEDURES TRAINER

We feel that there is a definite need for a HUD procedures trainer at at least the advanced trainer level. This airplane should be equipped with a full suite of head=up and head-down CRT displays and should be able to emulate the various symbologies in the fleet (although increased standardization should minimize this requirement). The mission of this airplane should be (1) to provide basic introduction to HUD instrument flying; (2) to provide recurrent HUD instrument checks; and (3) to develop adequate HUD instrument procedures. It should also include some form of computer navigation system to acquaint the student pilot with the

data entry and monitoring requirements of modern inertial navigational systems (INSs) and their computers.

A great deal of the problem inherent in modern military airplanes is the high workload of the weapon systems themselves. Often these require considerable effort in inputting data to the on-board computer and in monitoring the systems data. The skills needed to accomplish these tasks are not the same skills emphasized in flying training.

Many of the tasks required are weapon system specific. Nevertheless, there is a common thread of the problems. There is a need to learn how to prioritize attention and workload capacity to accomplish the primary job of the pilot -- keep the airplane from flying into the ground!

This training could be accomplished using a generic weapon system computer -- to teach the fledgling pilot how to allocate his cognitive resources to his tasks and maintain his awareness. This would be similar in scope to fighter lead-in training (LIT). In LIT, the student pilots fly generic mission profiles and use generic tactics in T-38s.

Perhaps the closest approach to this type of training is the low-level awareness taught at Tucson by the Air National Guard.

This may be expensive, but not as expensive as on the job training as is done today. Such a HUD procedures trainer would be cost effective in the long run -- even without considering the savings in lost airplanes and crew.

V. CONCLUSIONS

The following conclusions can be drawn:

- The HUD is not inherently unsafe and is quite suitable for use as a primary flight display in IMC.
- The use of air mass data vice inertial velocity vector data has certain advantages in some situations.
- Current military instrument training is inadequate both in terms of initial pilot training and recurrent training.
- The specific techniques required for head-up displays are exacerbated by the lack of adequate training. This lack of HUD training borders on the irresponsible.
- The use of a generic HUD procedures trainer is heavily recommended.
- A library of HUD symbologies should be developed for use in this trainer.

VII. REFERENCES

1 J. M. Naish, System for Presenting Steering Information During Visual Flight: Part I, The Position of Presented Information, RAE-TN-IAP-1132, October 1961

2 J. M. Naish, System for Presenting Steering Information During Visual Flight: Part II, The Form of the Presented Information, RAE-TN-IAP-1138, February 1962

3 J. M. Naish, System for Presenting Steering Information During Visual Flight: Part III, The Influence of Errors and Limitations, RAE-TR-64026, October 1964

4 A Comparison of Electronic World and Flight Director World Head-Up Display: Their Installation and Philosophy, Elliott Brothers ADD-229, April 1968

5 J. M. Naish, "The Flight Simulator in Display Research," Journal of The Royal Aeronautical Society, 68, 1964, 653-659

6 E. Fischer, R. F. Haines and T. A. Price, Cognitive Issues in Head-Up Displays, NASA-TP-1711, December 1980

7 R. L. Newman, Operational Problems Associated with Head-Up Displays During Instrument Flight, AFAMRL-TR-80-116, October 1980

8 J. F. Barnette, Role of Head-Up Display in Instrument Flight, AFIFC-LR-76-2, August 1976

9 R. L. Newman, Head-Up Display Design Guide, Crew Systems TR-87-15, June 1987

10 R. L. Newman and R. E. Bailey, Head-Up Display Dynamics Flight Tests, Crew Systems TR-87-12, June 1987

11 R. L. Newman and R. E. Bailey, Head-Up Display Accuracy Flight Tests, Crew Systems TR-87-13, June 1987

12 R. L. Newman, Evaluation of Head-Up Displays to Enhance Unusual Attitude Recovery, Crew Systems TR-87-14, June 1987

13 Proceedings of the HUD/Instrument Conference, Langley AFB, TAC Headquarters, June 1983

14 Flight Instrumentation Conference, Pentagon, US Air Force, June 1985

15 Spatial Disorientation Conference, Flight Dynamics Laboratory, AFWAL, October 1985

16 A. C. McTee, D. L. Carmack, and R. K. Taylor, HUD Investigation in Low Visibility, IPIS TR-71-3, June 1971

17 D. Hameluck and P. Stager, "The Peripheral Visual Horizon Display: A Review," Proceedings 4th International Symposium on Aviation Psychology, Columbus, April 1987

18 K. R. Woodruff, Use of Flight Path Angle on the Attitude Ball, Systems Research Laboratories TM-2, October 1970; Report for Contract F33615-69-C-1595

19 J. F. Barnette and G. Intano, Determining the Utility of Expanded Pitch Scale and Flight Path Angle as Display Parameters, AFIFC-TR-76-4, October 1976

20 G. Klopfstein, "Rational Study of Aircraft Piloting," INTRADOS, 1966; reprinted by Thomson-CSF

21 H. Suisse, Head-Up Display System -- PERSEPOLIS Symbology, Dassault Report DGT-16433, September 1979

22 "A Word from the Navy," ALPA Head-Up Display Newsletter, January 1979, pp. 30-31

22 A. J. Benson (ed.), The Disorientation Incident, AGARD-CP-95-Part I, March 1972; papers presented at Aerospace Medical Panel Specialist Meeting held in Luchon, France, September 1971

23 Aircraft Accident Report: China Airlines Boeing B747SP, N4522V, 300 NM Northwest of San Francisco, February 19, 1985, NTSB-AAR-86-03, March 1986

24 Aircraft Accident Report: Trans World Airlines Boeing B727-231, N54328, Berryville, Virginia, December 1, 1974, NTSB-AAR-75-16, November 1975

25 Boeing 727-100,G-BDAN, Accident Near Teneriffe North Airport, The Canary Islands, on 25 April 1980, Spanish Accident Investigation Commission Report, July 1981; in ICAO Aircraft Accident Digest No. 27, ICAO Circular 178-AN/111, 1984

26 "Jaguar Hit Trees," Flight International, 19 July 1986; Summary of RAF Accident Investigation Board investigating accident to RAF Jaguar GR.1A in West Germany, July 9, 1985

27 A. J. Benson, "Spatial Disorientation in Flight," in Aviation Physiology, J. A. Gillies (ed.), London: Pergamon Press, 1965, pp. 1086-1129

28 R. J. Randle, S. N. Roscoe, and J. Petit, Effects of Accommodation and Magnification on Aimpoint Estimation in a Simulated Landing Task, NASA-TP-1636, October 1980

29 R. L. Newman and T. G. Foxworth, A Review of Head-Up Display Specifications, Crew Systems TR-84-04, April 1984; final report for contract F33615-83-C-5124

30 P. R. Tyler and P. A. Furr, "Disorientation: Fact and Fancy," in The Disorientation Incident, AGARD-CP-95; Reference 1.

31 R. M. Taylor, "Some Effects of Display Format Variables on the Perception of Aircraft Spatial Orientation," AGARD Symposium on Human Factors Consideration in High Performance Aircraft, Williamsburg, April/May 1984

32 R. M. Taylor, "Attitude Awareness from Aircraft Head-Up Display," Proceedings Fourth International Symposium on Aviation Psychology, Columbus, April 1987

33 Display Factors for Electronic Flight Instrument Systems, FAA Draft Advisory Circular, June 1985

34 S. J. Monagan and R. E. Smith, "Head-Up Display Flight Tests," Proceedings 24th Annual Symposium Society of Experimental Test Pilots, Beverly Hills, September 1980, pp. 75-87

35 J. M. Naish, Properties and Design of the Head-Up Display, McDonnell-Douglas Report MDC-J1409, April 1968; revised February 1970; also published as Douglas Paper 4951

36 U. Freiburg, "Basic About Scale One-to-One Head-Up Display," Proceedings 15th Annual Symposium Society of Experimental Test Pilots, Beverly Hills, September 1971, pp. 77-85

37 S. N. Roscoe, "Bigness is in the Eye of the Beholder," Human Factors, 27, 1985, 615-636

38 J. H. Iavecchia, Response biases with Virtual Imaging Displays, NADC-85165, June 1985

39 J. H. Iavecchia, The Potential for Depth Perception Errors in Piloting the F-18 and A-6 Night Attack Aircraft, NADC Report, in preparation

40 U. Freiburg and S. Holmström, "An Ordinary 3-Axis Horizon Instrument Which Every Pilot Likes -- Can It Be Misleading and Dangerous? The Answer is 'Yes'," Proceedings 30th Annual Symposium Society of Experimental Test Pilots, Beverly Hills, September 1986, pp. 187-199

41 Head-Up Guidance System, Flight Dynamics, Inc. Pilot Guide, n. d.

42 R. L. Newman, <u>An Evaluation of the FDI Head-Up Display</u>, Crew Systems TM-87-04, January 1987

43 <u>Programme Simulateur -- Approche Automatique Mode Land</u>, Air Inter Manuel de L'Equipage Mercure, January 1979

44 <u>Instrument Flying</u>, AFM-51-37, July 1986

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